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Introduction: Weakly Ionized Plasmas for Propulsion Applications

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THIS special section is devoted to a group of emerging technologies centering on weakly ionized plasmas for propulsion enhancement. The ionization fraction of concern (i.e., the fraction of gas molecules that are ionized) ranges from as low as 10^{-8} to 10^{-2}, hence the term *weakly ionized*. The gas pressure in the plasmas can take almost any value. In applications to high-altitude flight, the static pressure is on the order of 10–100 torr, whereas combustion applications demand near-atmospheric or above-atmospheric pressures. The temperature of the gas can be near-ambient in low-pressure glow discharges, becomes 5000–10,000 K in arc or high-pressure microwave discharges, or reaches 20,000–30,000 K in laser-generated sparks. The plasmas can be generated by electric or electromagnetic fields, from dc to RF, short pulses, microwaves, and optical (laser) beams, or by various combinations of the preceding. In general, low-pressure plasmas tend to be uniform (diffuse) and nonequilibrium. The temperature of electrons and internal molecular modes can be very high, whereas the gas as a whole stays relatively cold. As the pressure and power loading increase, plasmas tend to become hotter, getting closer to thermal equilibrium, and break into channels (streamers and arcs). The reality, however, is more complex. In some devices, such as dielectric barrier discharges, nonequilibrium plasmas are generated even at atmospheric pressure, and in devices such as the gliding arc, the plasma evolves from near-equilibrium to quite nonequilibrium during each of the periodically repeating cycles.

What features or properties make weakly ionized plasmas interesting for propulsion and aerodynamic applications? The most obvious feature is heating: a consequence of Joule dissipation in an electrically conducting medium placed in an electric field. As a heating element, plasma has important advantages compared with conventional heaters. For example, even a surface electric discharge can effectively heat the gas flow much farther from the wall than a wall-imbedded conventional heater would. Microwave and laser beams can create plasmas and heat the gas even far from any surfaces, and the volume and shape of the heated region can, in principle, be adjusted. Because heated regions can significantly alter the flow by making the gas flow mostly around them, plasmas can form switchable, controllable, and tunable virtual bodies or surfaces. Such virtual surfaces can be deployed on demand for drag reduction, aerodynamic control (when applied asymmetrically), optimization of engine inlet performance, etc. It is the localized and transient deployment of plasma virtual surfaces that results in most interesting and complex interactions with gas flows while saving energy, compared with large-volume steady-state plasma utilization, and thus is especially promising for applications.

Another useful application of plasma heating is ignition. This may seem trivial; after all, spark plugs in conventional internal combustion engines are well-developed thermal plasma devices. However, thermal plasma ignition for scramjet engines is not that simple, because the ignition system would have to prevent the plasma from being easily blown away by the supersonic flow, and even if this problem is resolved, if not properly (and quite ingenuously) designed, the igniter would cause an unacceptably strong perturbation to the flow and loss of the stagnation pressure and would require extremely high power. As an example, plasma igniters based on subcritical microwave discharges are quite sophisticated.

In addition to heating, the presence of charged particles (electrons and ions) is another obvious, and very important, feature of plasmas. Charged particles can be acted upon by electric and magnetic fields, and this action can be transferred to the bulk gas by ion–molecule collisions. Thus, magnetohydrodynamic (MHD) and electrohydrodynamic (EHD) interactions can be used to exert forces and to decelerate or accelerate the gas in both inviscid core flows and viscous boundary layers. The magnitude of such interactions depends on the ionization fraction and the magnetic or electric field strength.

The ionization fraction can be quite high in shock and boundary layers at very high Mach numbers (such as those in reentry flight) or just downstream of ram/scramjet combustors if alkali vapor is added to the gas. In those regions, MHD interactions can be promising for electric power generation or acceleration of the flow, as well as for flow control. However, at Mach numbers below about 12 (and excluding the combustor or the region just downstream of it), the air is too cold for a significant thermal ionization, even with alkali seeding. The required level of ionization then has to be created and sustained by nonequilibrium (nonthermal) means and is associated with very substantial power budget and additional heating. Therefore, the efficiency of ionization (which can vary by orders of magnitude) is of first-order significance. In this regard, ionization by high-energy electron beams or by repetitive high-voltage nanosecond pulses is promising. In this special publication, both techniques are discussed.

Even with the most efficient ionization techniques, the power budget and additional heating associated with the ionizer normally limit the achievable level of ionization. To have a substantial MHD effect, one has to either use a very strong magnetic field (which is associated with some practical issues) or use the MHD interaction in a localized and transient regime (e.g., for boundary-layer control).

As for EHD interaction, it relies upon nonneutrality of the plasma and an electric field to impart momentum to the gas. Although EHD (or *ion wind*) phenomena have been known for many years, the last several years saw a surge of new interest in this type of interaction. This new boom is due to the asymmetric dielectric barrier discharge (DBD), a remarkably simple device that has been demonstrated to be very effective in delaying and controlling flow separation and perhaps even laminar-turbulent transition. Although details of the physics of DBD plasma actuators are still incompletely understood, the simplicity of these devices, their low power consumption, and the striking effectiveness in separation control bring these systems to the top of the list of plasma aerodynamics and plasma-assisted propulsion technologies that have near-term application prospects.

Another area in which nonequilibrium (nonthermal) weakly ionized plasmas are very promising is plasma-assisted combustion. Although heating induced by plasmas can ignite combustible mixtures, as mentioned, it is the presence of *hot* electrons in a cold gas that makes nonequilibrium plasmas quite interesting for promoting chemical processes such as combustion. Electron-impact dissociation, excitation, and ionization of molecules can generate chemically active species such as radicals and excited atoms and molecules, and those species can initiate or accelerate chemical reactions that would otherwise be nonexistent or slow at low temperature. A number of novel techniques, including (but not limited to) high-voltage nanosecond pulses and the so-called gliding arc have been shown to be quite effective in plasma-assisted combustion. Investigation of detailed mechanisms (often quite complex and nontrivial) of the coupled physical and chemical processes in those plasmas can potentially lead to their better understanding and help them become practical.

As a rule, weakly ionized plasma systems of interest to plasma aerodynamics and plasma-assisted combustion are extremely involved and represent a multidisciplinary field of study in which complex nonequilibrium plasma kinetics are coupled with electromagnetic phenomena, kinetics of excited species and radicals, and gas dynamics. Development and optimization of these systems should be based upon knowledge that must be gained through sophisticated modeling and diagnostic studies of well-defined and well-characterized systems. Such work, although it may seem to be too academic, is in fact necessary for practical applications. In this regard, it is worth noting that the progress in the physics of electric discharges and weakly ionized plasmas was always directly related to practical applications, from the development of fluorescent lights to electric-discharge molecular lasers. Plasma aerodynamics and plasma-assisted propulsion provide a new strong motivation for further development of electric-discharge physics, and the results are already being seen.

We hope that this special publication will provide readers with an overall picture of this emerging field, as well as with scientific and technological details on some of the key developments.

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